Particle dark matter searches through cross-correlations

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Dark Matter as a particle

DM evidence purely gravitational

If DM is a new particle, a non-gravitational signal (emission of some kind of radiation) is expected

We can exploit every structure where DM is present as a target, including the total average emission in the Universe (diffuse background)

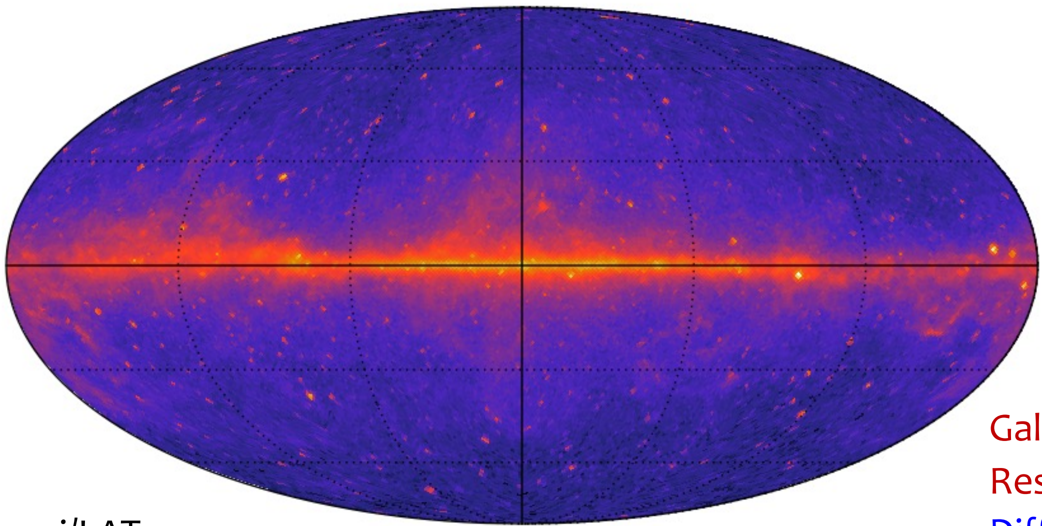
Unfortunately, DM signals are faint and astrophysical backgrounds dominant

Can we exploit more information?

- Indirect detection signals are intrinsically anisotropic

  (being produced by DM structures, present at any scale)

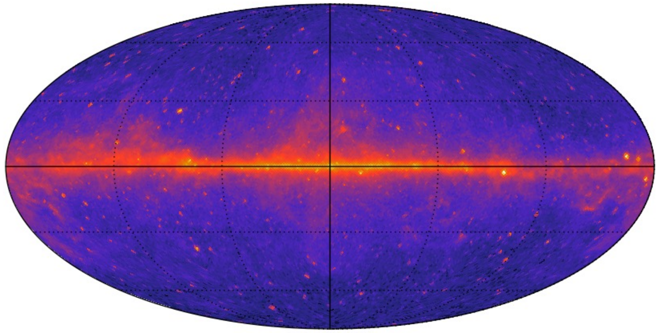
- Even though sources are too dim to be individually resolved, they can affect the statistics of photons across the sky, due to fluctuations in the emission field



Fermi/LAT map

Galactic foreground emission
Resolved sources
Diffuse Unresolved Gamma-Ray Backgound (∂UGRB)

Cross Correlations



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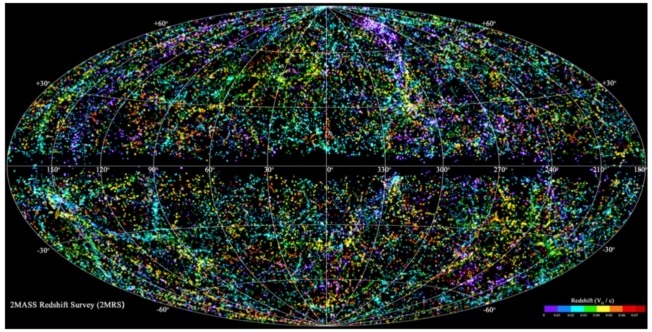


The fluctuations in the gamma-ray field need to be statistically correlated to the DM distribution in the universe (i.e. the DM fluctuations on top of a smooth Universe)

This cross-correlation is a statistical observable (it allows to infer global information, not identify individual sources) and exploits in a unified way two distinctive features of particle DM:

An electromagnetic signal, manifestation of the particle nature of DM

A gravitational probe of the existence of DM

It allows to 'add' distance (redshift) information to a probe (like gamma-rays) that does not have it

Cross-Correlations w/ Gamma Rays

Lensing observables

- Cosmic shear: directly traces the whole DM distribution

  Camera, Fornasa, NF, Regis, ApJLett 771 (2013) L5
  Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

- CMB lensing: traces DM imprints on CMB anisotropies

  NF, Perotto, Regis, Camera, Ap. J. Lett. 802 (2015) 1 L1
  NF, Regis, Frontiers in Physics, 2 (2014) 6

Large scale structure observables:

- Galaxy catalogs: trace DM by tracing light

  Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008) 123518
  Ando, Benoit-Levy, Komatsu, PRD 90 (2014) 023514
  NF, Regis, Front. Physics 2 (2014) 6
  Ando, JCAP 1410 (2014) 061

- Cluster catalogs

  Branchini, Camera, Cuoco, NF, Regis, Viel, Xia, ApJS 228 (2017) 1

- Neutral hydrogen (through HI intensity mapping)

  Pinetti, Camera, NF, Regis, JCAP 07 (2020) 044

- Cosmic voids

  Arcari, Pinetti, JCAP 11 (2022) 011

Measured cros-correlation signals

- w/ galaxy catalogs (3.5 σ (*)/8σ (^);)

(*) Cuoco+, ApJS 221 (2015) 29
(*) Regis+, Phys. Rev. Lett. 114, 241301 (2015)
Shirasaki+, Phys. Rev. D 92, 123540 (2015)
Cuoco+, ApJS 232, 1 (2017)
Ammazzalorso+, Phys. Rev. D 98, 103007 (2018)
(^) Paopiamsap+, Phys. Rev. D 109 (2024) 10, 103517

- w/ CMB-lensing (3.0 σ (*))

(*) Fornengo+, Ap. J. Lett. 802 (2015) 1 L1

- w/ cluster catalogs (4.7 σ (*))

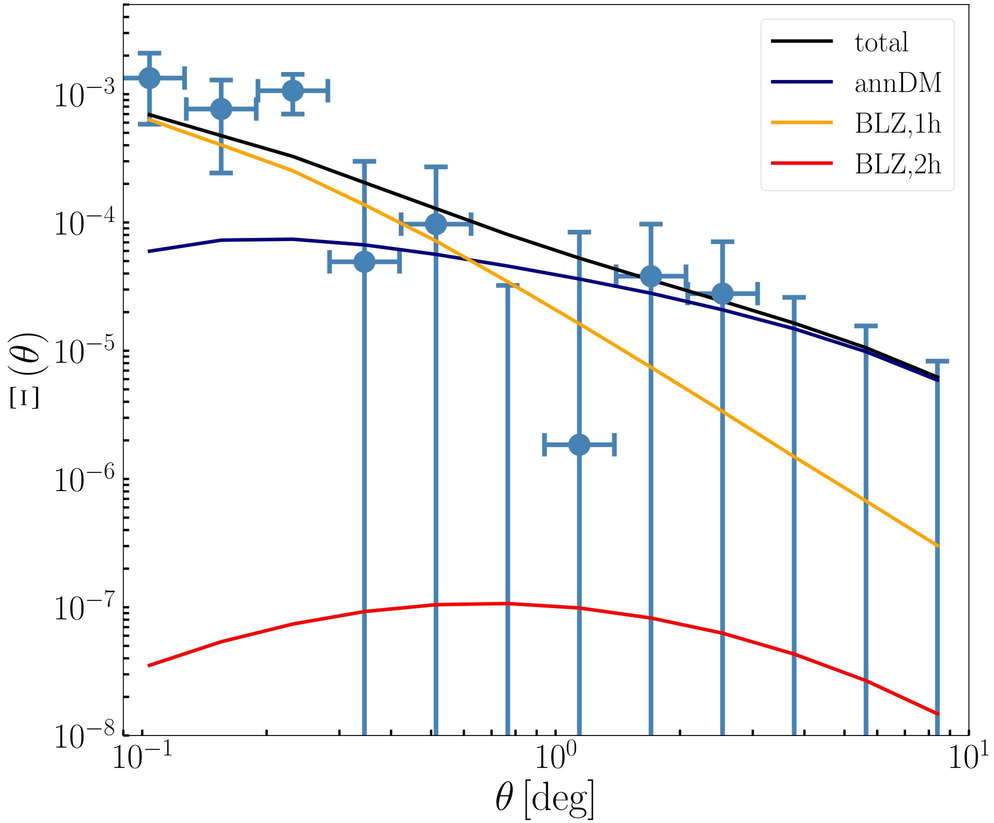
(*) Branchini+, ApJS 228 (2017) 1
Hashimoto, MNRAS 484, 5256 (2019)
Colavincenzo+, MNRAS 491, 3225 (2020)

- w/ cosmic shear (5.3 σ (*))

Shirasaki+, Phys. Rev. D 90, 063502 (2014)
Shirasaki+, Phys. Rev. D 94, 063522 (2016)
Troster, MNRAS 467, 2706 (2017)
Shirasaki+, Phys. Rev. D 97, 123015 (2018)
(*) Ammazzalorso+, PRL 124 (2020) 101102

Tangential shear: Fermi x DES (2020)

Ammazzalorso, Gruen, Regis, Camera, Ando, NF et al, PRL 124 (2020) 101102



DES 1 year (1786 deg^2)

Fermi 9 years

Evidence of a signal at 5.3σ

- The signal is mostly localized at small angular scales and high gamma-ray energies, with a hint of correlation at extended separation
- Blazar emission is likely the origin of the small-scale effect
- Statistics is still not enough to allow interpretation of the large-scale component and to determine impact on DM parameters

Tangential shear: Fermi x DES (2024)

Thakore, Negro, Regis, Camera, Gruen, NF + (to appear)

DES
- 3 years (4946 deg^2)
- GOLD catalog for galaxy selection
- METACALIBRATION shear catalog
- 4 redshift bins in (0,2)

Bin	No. of objects	$n_{\rm eff}$ (gal/arcmin^2)	σ_e	$z_{\rm mean}$
Full	100 204 026	5.590	0.268	0.633
1	24 940 465	1.476	0.243	0.336
2	25 280 405	1.479	0.262	0.521
3	24 891 859	1.484	0.259	0.742
4	25 091 297	1.461	0.301	0.964

Fermi
- 12 years
- Pass8 – R3
- SOURCEVETO v2 event class
- PSF 1 + 2 +3
- 9 energy bins in (631 MeV, 1 TeV)
- Mask: point sources in 4FGL-DR2 + $|b_{lat}| < 30°$

	Bin number								
	1	2	3	4	5	6	7	8	9
$E_{\rm min}$ [GeV]	0.631	1.202	2.290	4.786	9.120	17.38	36.31	69.18	131.8
$E_{\rm max}$ [GeV]	1.202	2.290	4.786	9.120	17.38	36.31	69.18	131.8	1000.0
$\theta_{\rm cont}$ 68% [deg]	0.50	0.58	0.36	0.22	0.15	0.12	0.11	0.10	0.10
Photon counts	351380	780646	551996	221181	81514	34374	10690	3352	1422

2-Point Correlation Estimator

Tangential ellipticity of source galaxy i
in redshift bin r
relative to pixel j

Photon intensity flux
in energy bin a
and pixel j

$$\Xi^{ar}(\theta) = \Xi^{\text{signal}}_{\Delta\theta_h, \Delta E_a, \Delta z_r} - \Xi^{\text{random}}_{\Delta\theta_h, \Delta E_a, \Delta z_r} = \frac{\sum_{i,j} e^r_{ij,\text{t}} \, I^a_j}{R \sum_{i,j} I^a_j} - \frac{\sum_{i,j} e^r_{ij,\text{t}} \, I^a_{j,\text{random}}}{R \sum_{i,j} I^a_{j,\text{random}}}$$

Angular bin

Energy bin a

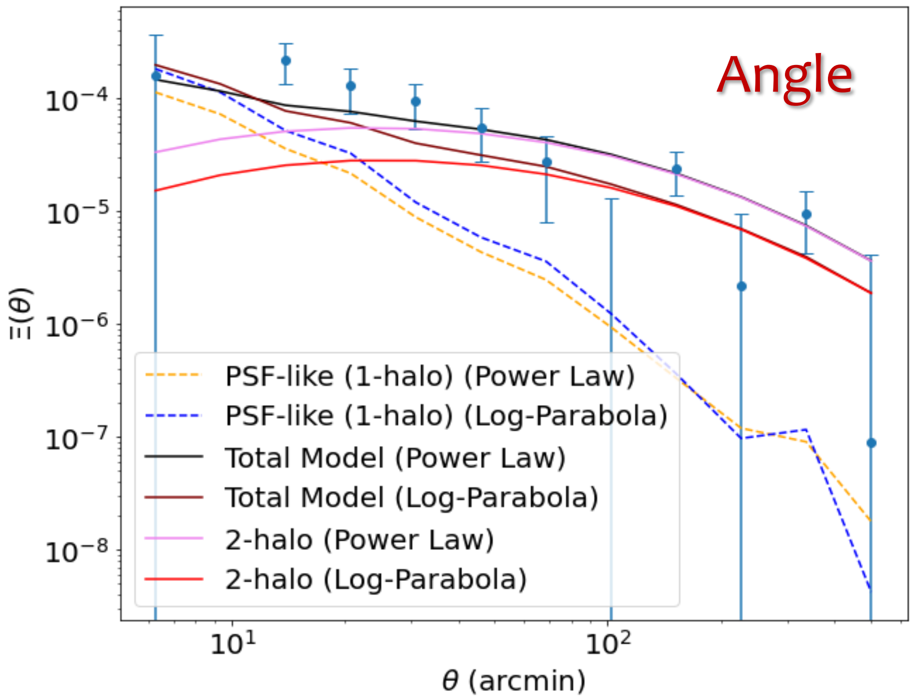
Redshift bin r

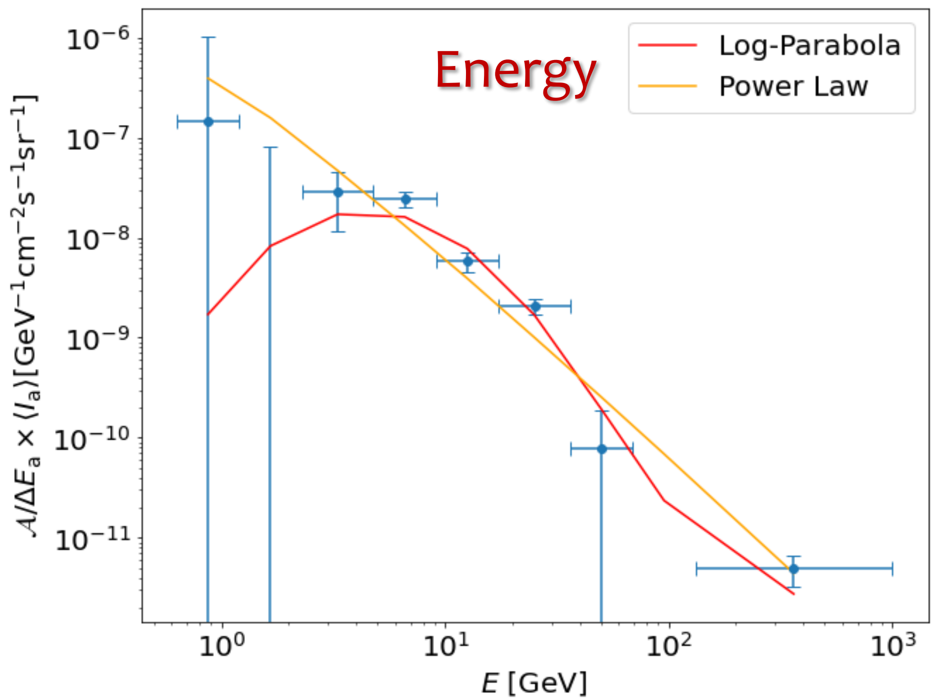
Sum over umasked pixels and DES sources
R: mean response (bias correction)

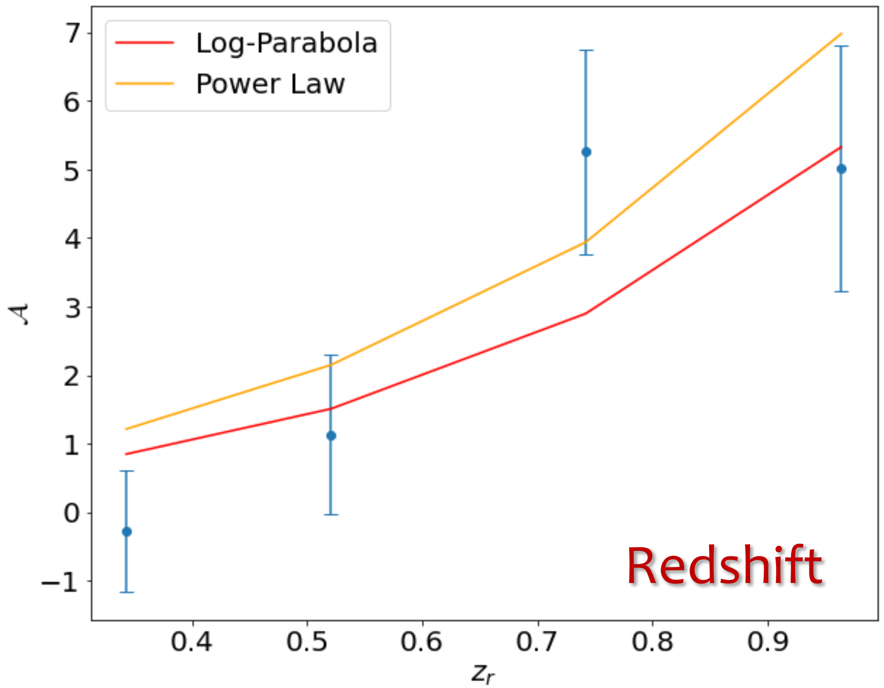
Random term, subtracted from the signal to reduce additive shear systematic effects, random very-large-scale structures or chance shear alignments relative to the mask (lowers the variance)

Analysis performed in:

- 12 log-spaced angular bins in (5, 600) arcmin
- 9 photon energy bins
- 4 redshift bins


Angle
PSF-like (1-halo) (Power Law)
PSF-like (1-halo) (Log-Parabola)
Total Model (Power Law)
Total Model (Log-Parabola)
2-halo (Power Law)
2-halo (Log-Parabola)
$\Xi(\theta)$
θ (arcmin)


Energy
Log-Parabola
Power Law
$\mathcal{A}/\Delta E_a \times \langle I_a \rangle [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$
E [GeV]


Log-Parabola
Power Law
Redshift
$\mathcal{A}$
z_r

Phenomenological Models

Model A: Power-law in energy

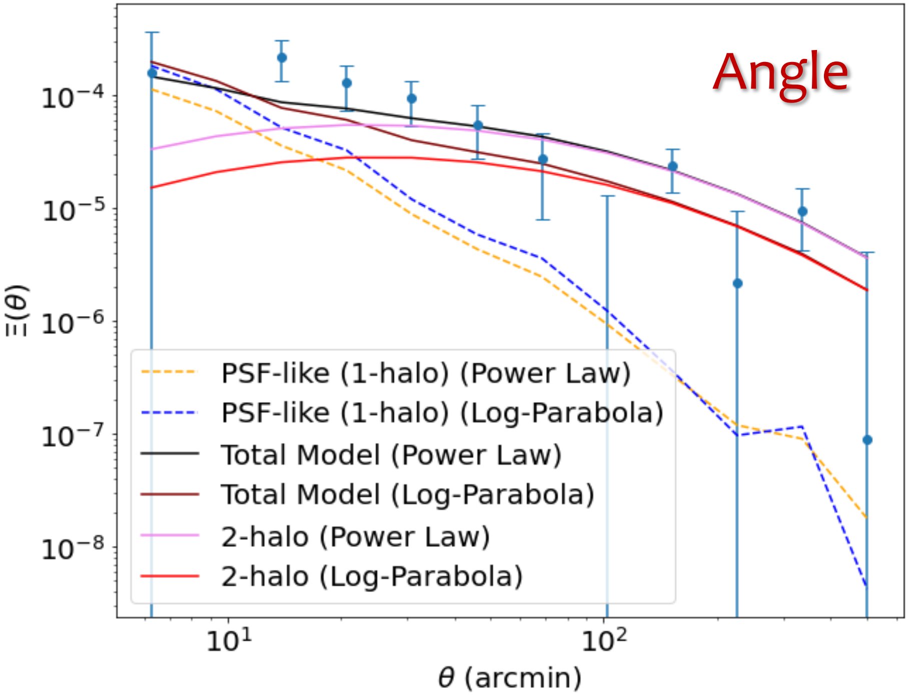
$$\Xi^{ar}_{\rm pl}(\theta)\ \langle I_a\rangle = A_1 E_a^{-\alpha_1}(1+z_r)^{\beta_1}\hat{\Xi}^{a}_{\text{PSF-like}}(\theta) + A_2 E_a^{-\alpha_2}(1+z_r)^{\beta_2}\hat{\Xi}^{ar}_{\text{2h-like}}(\theta)$$

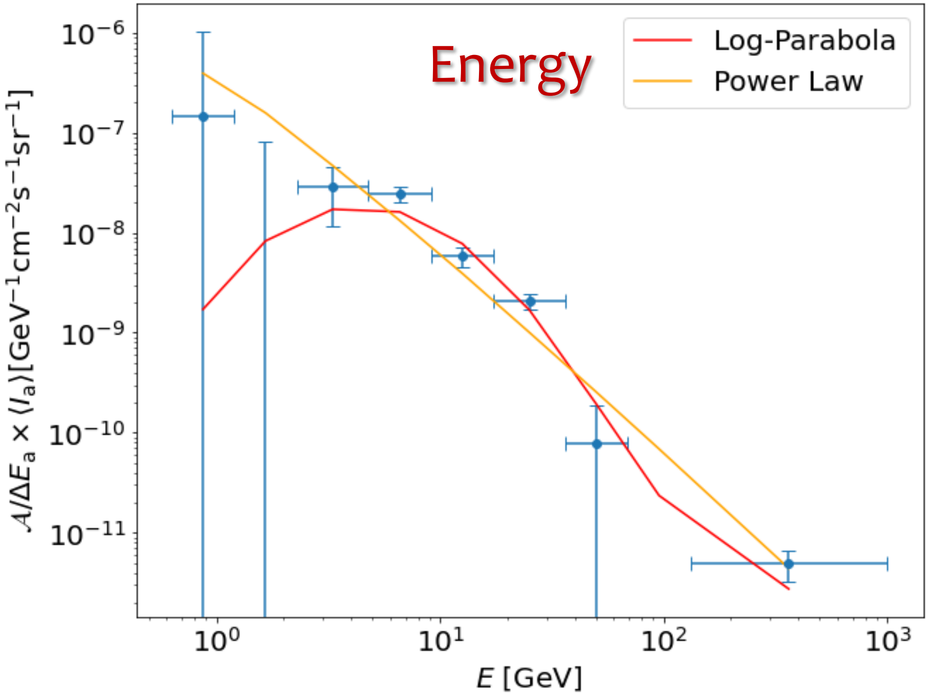
point-like large-scale

Model B: Log-Parabola in energy

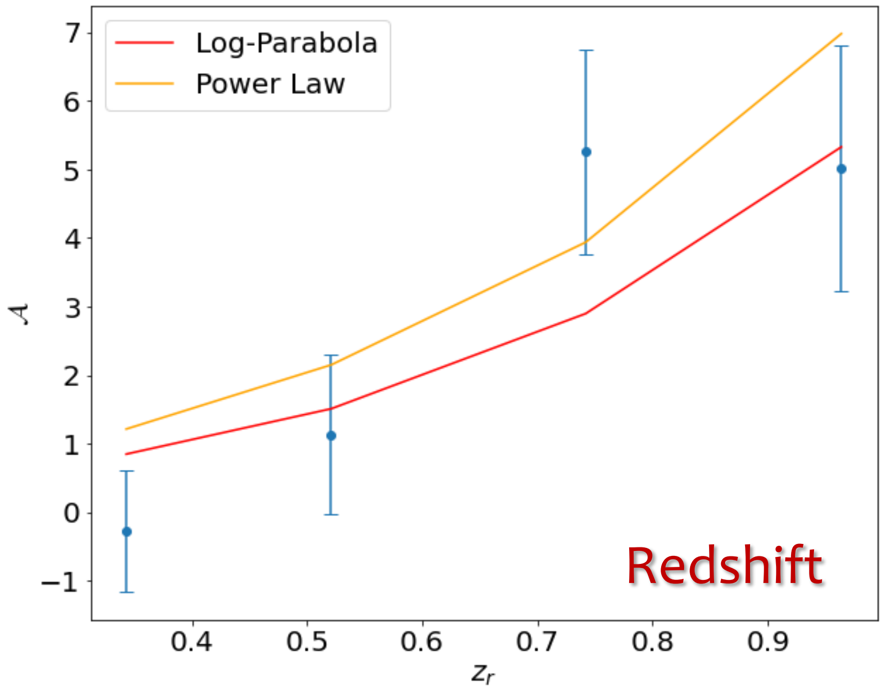
$$\Xi^{ar}_{\rm lp}(\theta)\ \langle I_a\rangle = A_1(E_a/E_0)^{-\alpha_1+\gamma_1\log(E/E_0)}(1+z_r)^{\beta_1}\hat{\Xi}^{a}_{\text{PSF-like}}(\theta) \quad \text{point-like}$$

$$+A_2(E_a/E_0)^{-\alpha_2+\gamma_2\log(E/E_0)}(1+z_r)^{\beta_2}\hat{\Xi}^{ar}_{\text{2h-like}}(\theta) \quad \text{large-scale}$$





B
A



	Data set						
	Full	Low-z	High-z	Low-E	High-E	Small-θ	Large-θ
$\Delta\chi^2_{\rm lp}$	78.92	3.40	75.28	23.29	55.36	5.82	73.73
$\mathrm{SNR}_{\rm lp}$	**8.88**	2.45	8.70	4.89	7.49	2.42	8.58
$\Delta\chi^2_{\rm pl}$	51.43	0.84	53.66	15.77	38.72	8.72	47.32
$\mathrm{SNR}_{\rm pl}$	**7.17**	1.66	7.34	4.03	6.24	2.96	6.88

B

A

Evidence for a signal increased to 8.9 σ / 7.2 σ

Comments

- Clear evidence for the presence of a cross-correlation signal
- The signal is mostly concentrated at:
  - High energies
  - Large angular scales
  - High redshift
- Higher significance from higher redshift bins is somewhat expected because those bins have a higher lensing signal being integrated over longer distances
- The evidence for correlation at large angles suggests that the measurement is not dominated by few very massive and very bright objects, but rather it comes from a clustered population of extragalactic sources.
- The evidence at large energies points towards an interpretation in terms of sources with hard energy spectrum (low-energies have low significance, due to the degradation of the Fermi energy resolution below few GeV)
- The hard spectrum suggests a possible preference for blazars, rather than star-forming galaxies or misaligned AGNs, although its curvature might be indicative of more than one component

Physical Models

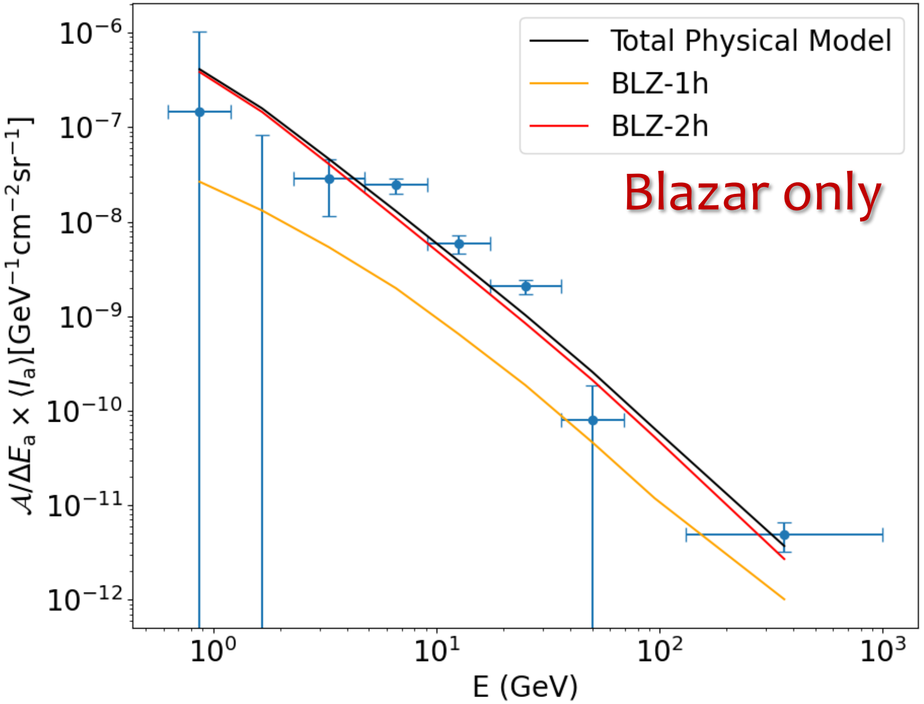
Blazar Models

$$\Xi^{ar}_{\rm phys}(\theta)\ \langle I_a\rangle = A^{\rm 1h}_{\rm BLZ}\,\hat{\Xi}^{ar}_{\rm BLZ,1h}(\theta,\mu_{\rm BLZ},p_1) + A^{\rm 2h}_{\rm BLZ}\,\hat{\Xi}^{ar}_{\rm BLZ,2h}(\theta,\mu_{\rm BLZ},p_1)$$

Blazar + DM Model

$$\Xi^{ar}_{\rm phys}(\theta)\ \langle I_a\rangle = A^{\rm 1h}_{\rm BLZ}\,\hat{\Xi}^{ar}_{\rm BLZ,1h}(\theta,\mu_{\rm BLZ},p_1) + A^{\rm 2h}_{\rm BLZ}\,\hat{\Xi}^{ar}_{\rm BLZ,2h}(\theta,\mu_{\rm BLZ},p_1) + A_{\rm DM}\,\hat{\Xi}^{ar}_{\rm DM}(\theta;m_{\rm DM})$$

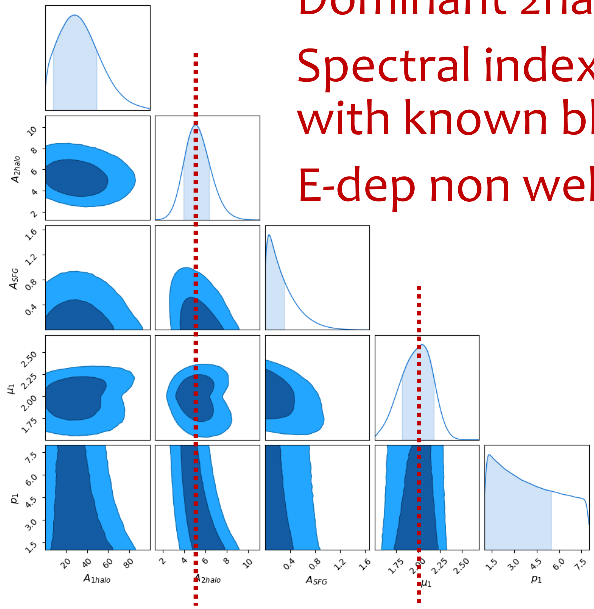
Both have been physically modeled according to PRL 124 (2020) 101102

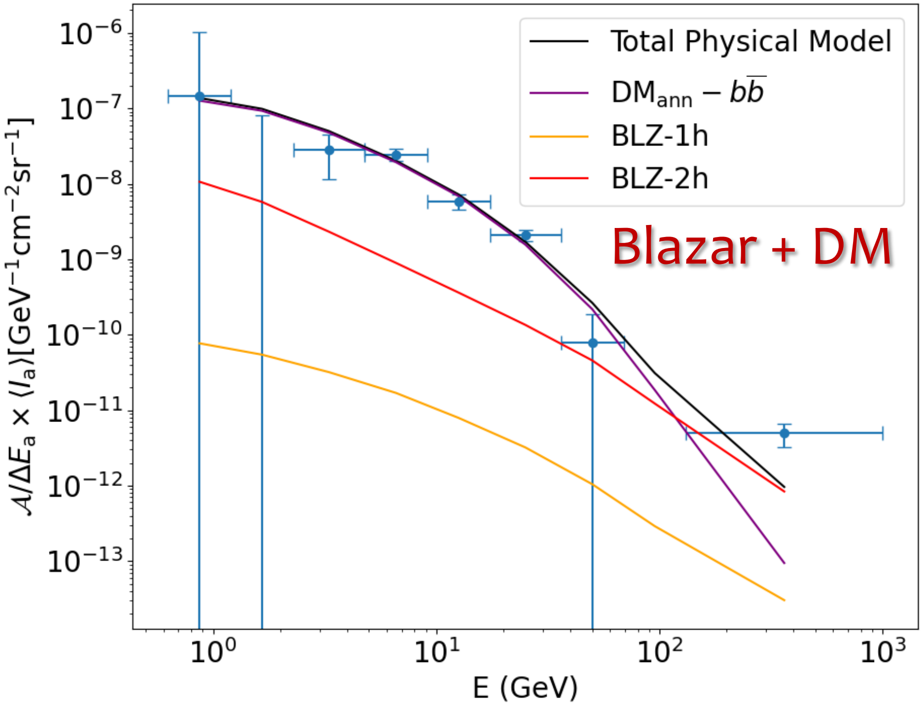


Dominant 2halo component

Spectral index consistent with known blazar

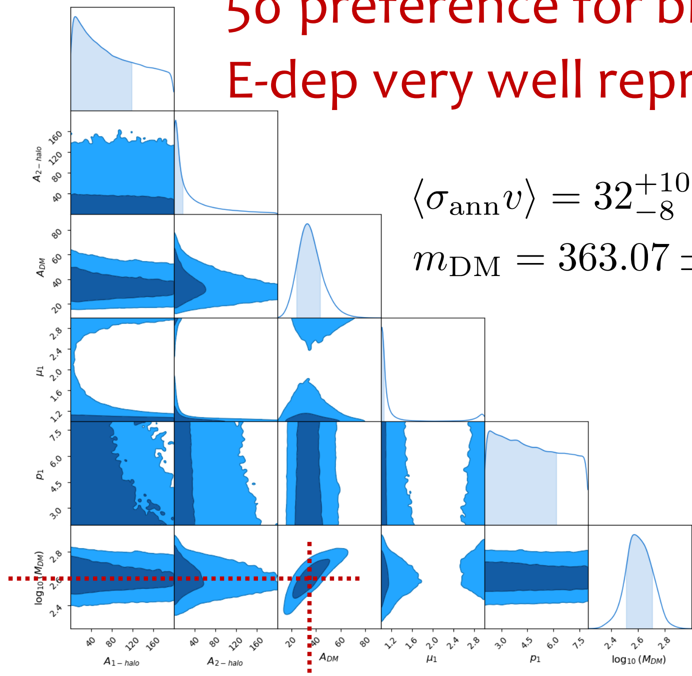
E-dep non well reproduced





5σ preference for blazar + DM

E-dep very well reproduced



$$\langle \sigma_{\rm ann} v \rangle = 32^{+10}_{-8} \, \langle \sigma_{\rm ann} v \rangle_{\rm th}$$

$$m_{\rm DM} = 363.07 \pm {}^{138.10}_{39.48} \ {\rm GeV}$$

Conclusions

- Clear evidence for the presence of a cross-correlation signal between cosmic shear and the cosmological gamma-ray background radiation, for angular scales up to a few hundreds of arcmins and for gamma-ray energies in (few GeV, 1 TeV)

- The statistical evidence is 8.9σ [7.2σ] for a curved [power-law] energy spectrum

- The signal is mostly concentrated at:
  - High energies
  - Large angular scales
  - High redshift

- Since a non-zero curvature energy spectrum is a better description of the signal, a physical interpretations where the signal is uniquely due to an unresolved blazar component seems less promising, while an interpretation with multiple sources looks favoured